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Distance-Based Energy-Efficient Opportunistic Broadcast Forwarding in Mobile Delay Tolerant Networks

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***Abstract*—Mobile relay-assisted forwarding in delay tolerant networks can improve the network capacity and the packet delivery ratio, but meanwhile may significantly increase energy consumption at system level. In this paper, we propose a distance-based energy-efficient opportunistic forwarding (DEEOF) framework for the broadcast transmission in mobile delay tolerant networks. DEEOF strikes a balance between energy consumption and network performance by maximizing the energy efficiency while maintaining a high packet delivery ratio. In the proposed algorithms, we define the metric of the forwarding equivalent energy-efficiency distance (FEED) for broadcast transmission to quantify the transmission distances achieving the same energy efficiency at different time instances, or with different numbers of the relays in the source's transmission radius. Based on the concept of FEED, we propose two DEEOF algorithms for opportunistic broadcast forwarding, which makes the forwarding decision by comparing the current energy efficiency with the estimated future expectation and distribution, respectively. The performance improvement of the proposed DEEOF algorithms is also demonstrated by simulation, especially for the cases in which the source has very limited battery reserves.**

I. Introduction

Node mobility was considered conventionally as an obstacle which needs to be intelligently overcome for seamless communication between nodes. Recently, it has been recognized that mobility can be exploited to improve the network performance. Grossglauser and Tse [1] introduced the advantages of mobility in mobile ad hoc networks. A significant performance gain is obtained through the exploitation of the time variation of the users' location and channel quality due to mobility. The multiuser diversity is exploited by forwarding the packets to mobile relays for additional "routes" between the source and the destination. Two-hop routes are sufficient to achieve the maximum throughput capacity of the network within the limits imposed by the interference model.

In mobile delay tolerant networks (DTNs) [2] in which mobile nodes can store and forward data, the mobility can be utilized in the following fashion: The source sends the packet to relays when they move close to each other; then the packet is stored and brought by the mobile relays to the area close to the destination. In this scenario, it is important to explore the problem of how mobility can be exploited to increase energy efficiency without degrading significantly the network performance in terms of the packet delivery ratio. In order to exploit node mobility to increase energy efficiency, the source should determine whether to broadcast the packet to relays or wait for a possible better opportunity in the future when the relays move closer so as to save transmission energy.

Due to the uncertainty of node mobility, the intermittent connectivity between two mobile nodes is random. The forwarding algorithms for DTNs usually spawn and keep multiple copies of the same packet in different nodes to increase the packet delivery ratio [3]. Obviously, it is not necessary to send as many copies as possible with the consideration of network cost, e.g., energy consumption, limited radio resources. Opportunistic forwarding that relies on probability metrics, such as time elapsed since last encounter [4], social similarity [5], geometric distance [6], etc., tries to achieve short packet delivery delay with relatively low transmission cost. Opportunistic forwarding is an efficient approach to achieve a balance between packet delivery delay and energy consumption, given the fact that short delivery delay is obtained at the expense of higher cost.

The focus of this paper is to investigate opportunistic forwarding by focusing on energy efficiency. Intuitively, we can take full advantage of node mobility without the delay consideration by letting the node forwarding the packets when the distance between the transmitter and receiver is infinitely close, which guarantees the lowest total energy consumption. However, this is not practical because each packet has a tolerant delay, i.e., the maximum time that the packet should be delivered to the destination, which depends on different service requirements. In this paper, we consider the energy-delay tradeoff and develop an optimal opportunistic forwarding strategy with high energy efficiency under the delay constraint. There are several technical challenges in our design:

- **Fundamental Delay-Energy Tradeoff**: The source waits

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for a transmission opportunity with lower energy consumption at the expense of reducing the probability of reaching the destination before the tolerant delay. Besides the transmission time, Another important issue for the delay-energy tradeoff is the transmission power, which should be determined according to the locations of all the relays inside the transmission range. The relationship between delay and energy is not straightforward in opportunistic broadcast forwarding.

- **Time-Varying Properties due to Node Mobility**: The transmission power to reach the relays varies in time and is related to the distance between the source and relays. Moreover, successful delivery also depends on the time difference to the tolerant delay constraint. Such time-varying property makes the forwarding decision difficult.
- **Performance Correlation Between Relays**: The energy efficiency of forwarding the data to a user is not independent but related to the data forwarding to other relays with broadcast transmission. In addition, the number of the mobile relays having the data affect the performance as well. Thus, an opportunistic forwarding scheme should inject the appropriate number of copies into the network.

To address the above design challenges, we first propose the concept of *forwarding equivalent energy-efficiency distance (FEED)* for broadcast transmission to establish the relationship between the node distance and the delay for the equivalent energy efficiency. The nearer the relays are or the earlier the time of forwarding is, the less energy the nodes consume. The FEED for broadcast transmission gives a comparison metric on the energy efficiency when the node distance, the delay time, or the number of the relays in the source's transmission radius is different, which helps the design of energy-efficient opportunistic forwarding. Utilizing the broadcast nature of wireless networks, we leverage the node mobility to develop two *distance-based energy-efficient opportunistic forwarding (DEEOF)* algorithms for opportunistic broadcast forwarding, which significantly improve the energy efficiency, while achieving a high packet delivery ratio.

The rest of this paper is organized as follows. Section II summarises the related work. Section III describes the system model. Section IV gives the problem formulation. Section V introduces the concept of the FEED. In Section VI and Section VII, the two DEEOF algorithms for the broadcast transmission are presented and analyzed. In Section VIII, the two DEEOF algorithms for the broadcast transmission are extended to the DTNs with CSMA-like protocols. Section IX evaluates the proposed algorithms by simulation. Finally, the paper is concluded in Section X.

II. Related Work

DTNs can exploit the opportunistic connectivity and node mobility to provide communication service in some highly challenged wireless networks. The applications of DTNs include large-scale disaster recovery networks, sensor networks for wildlife monitoring, ocean sensor networks, vehicular networks, and social networks. For various service requirement in different networks, the tolerant delay ranges from a few seconds to a few days. One of the most extensively explored packet forwarding schemes in DTNs is epidemic forwarding [3], in which the packets at relays are forwarded to all neighbors. Although this flooding-based scheme can achieve a high packet delivery ratio, it causes significant energy waste and suffers from poor scalability in large-scale networks. Over the past few years, significant research efforts have been devoted to opportunistic forwarding [7]-[9], trying to reduce the number of packets while retaining a relatively high delivery probability. Groenevelt and Nain [10] propose a two-hop forwarding algorithm, in which only the source of the message can replicate it, whereas the other nodes can only forward it to the destination. Liu and Wu [11] provide an optimal forwarding protocol which maximizes the expected delivery rate while satisfying the constant on the forwarding times per message. They propose the optimal probabilistic forwarding protocol, which makes optimal forwarding decisions by modeling forwarding as an optimal stopping problem. Also, some researchers study opportunistic forwarding in DTNs from a social networking perspective. Most of them use the mobile users' social features [13], community properties [14][15], as well as the mobility of the mobile users [16][17] to enhance the forwarding protocols.

Recently, energy efficiency has attracted a lot of research attention [18]. The work reported in [19] studies the optimal decentralized stochastic control with the energy constraint and analyzes the optimal policies for routing control based on sample path techniques. Similarly, the authors of [20] introduce a continuous-time Markov model to analyze the problem of the energy-efficient optimal opportunistic forwarding policies in DTNs. Mao *et al.* [21] address the problem of selecting and prioritizing the forwarding list to minimize the total energy cost of forwarding data to the sink node in wireless sensor networks and present an energy-efficient opportunistic routing strategy. An opportunistic and energy efficient routing protocol, which introduces a novel greedy forwarding algorithm and an efficient self-suppression scheme in multi-hop wireless networks, is proposed in [22]. The optimal opportunistic epidemic forwarding with energy constraint is investigated in [23] and [24]. By introducing a continuous time model, the authors of [23] obtain the optimal static and dynamic policies for multi-message forwarding. The authors of [24] propose an optimal energy-dependent message forwarding in energy-constrained DTNs by using a deterministic stratified epidemic model and prove that dynamic optimal strategies follow simple threshold-based rules. Some studies have investigated the contact-probing process of opportunistic forwarding to save energy in DTNs [25][26]. Furthermore, the tradeoff between delivery delay and energy consumption is studied for DTNs in [27] and [28]. Neglia and Zhang [27] present an analytical study on the tradeoff between delivery delay and energy consumption for epidemic routing in DTNs where all the nodes have perfect knowledge of the system status, in which the optimal forwarding policy is a threshold policy and the threshold is the number of copies in the network. The authors of [28] study the tradeoff between delivery delay and energy consumption in DTNs with two-hop relaying. They formulate the controlled forwarding

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problem as a partially observable Markov decision process and derive monotonicity results for the value function and the optimal policy. However, the existing works do not exploit the time-varying distance between mobile nodes. The distance of wireless transmission affects the energy consumption of data forwarding significantly, so it is necessary to forward the data opportunistically based on the distance for improving the energy efficiency, which is just the focus of this paper.

In our earlier work [29][30], we provide some preliminary results on distance-based energy-efficient opportunistic forwarding for unicast transmission. By exploiting the broadcasting nature of wireless transmission, the source can forward the data to multiple relays within its transmission range, which improved the energy efficiency significantly. In this paper, we further investigate the opportunistic broadcast forwarding and address the technical challenges induced by broadcast transmission.

III. System Model

Consider a mobile DTN situated in an $L \times L$ area composed of a set $\mathcal{N}$ of N nodes. Any two nodes can communicate with each other once moving into the maximum transmission range, denoted by R. We assume that all nodes in the network move independently, with a speed of $v \in [v_{min}, v_{max}]$ and their mobility patterns [31] are independent and identically distributed (i.i.d.).

Throughout our paper, we focus on a communication session between a source and a destination in the network. The source delivers data packets to the destination by distributing multiple copies of a packet to different relays. The tolerant delay of packet delivery is denoted as T. In the paper, two-hop forwarding [10] is adopted to limit the number of message transmissions and consequently the energy consumption. In this context, the nodes establish communication contact when they are inside the maximum transmission range of each other [19][20]. By an 1-bit message, the relay knows if the destination has already received the packet copy, and thus, only the relay which reaches the destination firstly transmits the packet. Also, the energy consumption is ignored for the control signaling, e.g., discovering the nodes inside the transmission region.

Time is slotted with the slot duration U. Consider a particular packet to be sent by the source at time $t_0 = 0$, the source probes the network to check if any relays move into its transmission region at the beginning of each slot $t_0 = 0, t_1 = U, t_2 = 2U, \cdots, t_k = kU, \cdots$, until T, when the packet should be dropped. The scenario with broadcast forwarding that a single forwarding can transmit the packet copies to multiple relays within the transmission range of the source is considered. If any relays are detected within the maximum transmission radius R, the source should determine whether or not to forward the packet copy to the relays without a packet copy with a appropriate transmission radius. When the relays receive the packet copy from the source and move into the transmission range of the destination, the relays forward the packet to the destination.

IV. Energy-efficient Opportunistic Forwarding: Problem Formulation

In this section, we formulate the energy-efficient opportunistic forwarding problem as a multi-objective optimization problem.

The average large-scale path loss for an arbitrary T-R separation is expressed as a function of their distance:

$$\overline{PL}(d) \propto \left(\frac{d}{d_0}\right)^{\alpha}, \tag{1}$$

or in the equivalent dB form,

$$\overline{PL}[dB](d) = \overline{PL}[dB](d_0) + 10\alpha \log\left(\frac{d}{d_0}\right), \tag{2}$$

where α is the path loss exponent which indicates the rate at which the path loss increases with distance, d_0 is the close-in reference distance which is determined by measurements close to the transmitter, and d is the T-R distance. The bars in (1) and (2) denote the ensemble average of all possible path values for a given value of d. The value of α depends on the specific propagation environment. With the given received power, the transmission power, denoted as P_t, is proportional to the α-th power of the T-R distance, which is expressed as

$$P_t = d^{\alpha} \cdot c, \tag{3}$$

where c is a constant.

Let $0 \leq t_{i,j}(1) < t_{i,j}(2) < \cdots$ denote the successive meeting times between node i and j ($i \neq j$), that is, the time when two nodes establish communication contact. $\tau_{i,j}(n) \triangleq t_{i,j}(n+1) - t_{i,j}(n)$ is defined as the n-th *inter-meeting time* (IMT) between node i and j. Transmissions between two nodes only occur at meeting times. We assume that the propagation time of a packet between two nodes is negligible with respect to the IMT. This is the case when the transmission radius is much smaller than the size of the area. The IMT in our model is assumed to be exponentially distributed with parameter λ, which is equal to $1/\mathbb{E}(\tau)$. This assumption is valid for various mobility models such as random walk, random direction, random waypoint, etc.[1] The exponential IMT for mobility models is analyzed in [10]; it can be seen that the parameter of IMT distribution λ is a function of the transmission radius of nodes, so it is denoted as λ_d when the transmission radius is d in the following.

Consider a packet arriving at the head of the outgoing queue of the source at time $t_0 = 0$. An opportunistic forwarding policy, denoted as ρ, is formally defined as

$$\rho \triangleq [E(t_1), E(t_2), \cdots, E(t_K)], \tag{4}$$

where the forwarding action $E(t_k)$ denotes the energy consumption of the source forwarding the packet at time t_k, and K denotes the largest integer not larger than T/U. Thus, if the source broadcasts the packet copy to relays with a transmission

[1]There exist studies based on the traces collected from real-life mobility [32] which argue that IMT may follow a power-law distribution, whereas the authors of [33] have shown that these traces and many others exhibit exponential tails after a cutoff point. Thus, we choose to stick to the exponential IMT assumption, which makes our analysis tractable.

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radius d at time t_k, $E(t_k) = d^\alpha \cdot c$. $E(t_k) = 0$ indicates that the source does not broadcast the packet copy at time t_k.

Given a policy ρ, let $S(t_k)$ denote the delivery predictability, which is the packet delivery ratio estimated by the source at time t_k. In each probing instance t_k, the source can establish communication contact with all the relays that move into its transmission region. Then it selects the relays without a packet copy and makes the decision of whether or not to broadcast the packet copy to them. As a result, the relays consume a fixed amount of energy for delivering a packet successfully. Thus, we account for the energy consumption of only the source in this paper.

Without loss of generality, assume that at time $t_k = kU$, the source detects a number of relays in its maximum transmission radius R, among which q relays without any packet copy have a source-relay distance shorter than d. The delivery predictability is $S(t_{k-1})$ at time t_{k-1}. Since the IMT between a relay and the destination is exponentially distributed with parameter λ_R as assumed previously, the probability of a relay meeting the destination before T is $1 - e^{-\lambda_R(T-t_k)}$. Now consider the moment t_k; if the source decides to forward the packet copy to q relays with a transmission radius d, the delivery predictability at time t_k can be derived as

$$S(t_k) = 1 - (1 - S(t_{k-1})) \cdot e^{-\lambda_R(T-t_k)\cdot q}, \qquad (5)$$

meanwhile, the energy consumption is $E(t_k) = d^\alpha \cdot c$. The cumulated energy consumed in forwarding the packet by the source at time t_k is denoted as $E_c(t_k) = \sum_{i=1}^{k} E(t_i)$. We define the energy efficiency $\eta(t_k)$ as $\eta(t_k) \triangleq S(t_k)/E_c(t_k)$. In this paper, we are interested in seeking the optimal opportunistic forwarding policy that maximizes $\eta(T)$ and $S(T)$. The optimization problem is formulated formally as follows:

$$\begin{aligned} \max_{\rho} \quad & [\eta(T), S(T)] \\ s.t. \quad & E_c(T) \le E, \end{aligned} \qquad (6)$$

where E denotes the total battery reserve of the source.

V. Forwarding Energy Efficiency Metric: Forwarding Equivalent Energy-Efficiency Distance

The basic idea of the developed algorithms is to forward the packet when the forwarding action can maximize the increment of the packet delivery ratio per unit of energy. In other words, the source seeks to use its energy in the most efficient way. To streamline our analysis, we start by introducing the concept of forwarding energy efficiency. Then taking into account the user mobility, we coin the metric of the forwarding equivalent energy-efficiency distance (FEED) to quantify the forwarding energy efficiency.

A. Forwarding Energy Efficiency

To optimize the energy efficiency of the forwarding policy, we quantify the energy efficiency of a single forwarding action by the following definition:

Definition 1 (Forwarding Energy Efficiency): Consider any probing time instance t_k. Let $\Delta S(t_k) \triangleq S(t_k) - S(t_{k-1})$ denote the increment of the delivery predictability if the source forwards the packet copy. The forwarding energy efficiency, denoted as $\eta_f(t_k)$, is defined as

$$\eta_f(t_k) \triangleq \frac{\Delta S(t_k)}{E(t_k)}. \qquad (7)$$

Specifically, for the broadcast transmission, if the source determines to forward the packet copy to the nearest q relays in a broadcast manner with a distance d at time t_k, it will incur an energy consumption of $E(t_k) = d^\alpha \cdot c$, with the delivery predictability changing to $S(t_k) = 1-(1-S(t_{k-1}))\cdot e^{-\lambda_R(T-t_k)\cdot q}$. Thus the forwarding energy efficiency of the broadcast is expressed as

$$\begin{aligned} \eta_f(t_k) &= \frac{S(t_k) - S(t_{k-1})}{E(t_k)} \\ &= \frac{(1 - S(t_{k-1})) \cdot (1 - e^{-\lambda_R(T-t_k)\cdot q})}{d^\alpha \cdot c}. \end{aligned} \qquad (8)$$

■

Remark 1: For the broadcast transmission, increasing transmission power at the source can enable more relays in its transmission radius receive the packet copy, but this will incur more energy consumption. Therefore, the source should choose the appropriate transmission radius to maximize the forwarding energy efficiency of the broadcast. ■

Taking the node mobility into account, relays may move closer to the source in the future, resulting in a shorter source-relay distance d' ($d' < d$). Consequently, forwarding a packet copy at this moment may consume less energy; in other words, the forwarding energy efficiency may be higher than $\eta_f(t_k)$. Therefore, at time t_k, the source has to predict the forwarding energy efficiency at time t_n ($n = k+1, k+2\cdots$). Here, we assume that the predicted period, which is denoted as δ, is

$$\delta = \frac{E(t_k)}{E - E_c(t_{k-1})} \cdot (T - t_k). \qquad (9)$$

It can be seen that the predicted period is related to the residual energy and the residual packet lifetime. When the source has a little residual energy or plenty of residual packet lifetime, the source should have a long-term consideration about how to use the residual energy efficiently while maintaining a high packet delivery ratio. Actually, δ has an impact on the tradeoff between the energy efficiency and packet delivery ratio. A longer predicted period means that the source values the energy efficiency more than packet delivery ratio, and vice versa.

B. Forwarding Equivalent Energy-Efficiency Distance (FEED)

To further quantify the impact of mobility on the forwarding energy efficiency, we propose the concept of the FEED in this subsection.

Definition 2: (Forwarding Equivalent Energy-Efficiency Distance): Consider the time instance t_k with a transmission radius d, the FEED of the broadcast, denoted as $\widehat{d}_k^{n,i}(d)$, is defined as the transmission radius with which by broadcasting the packet copy to i relays at time t_n ($n = k+1, k+2\cdots$,

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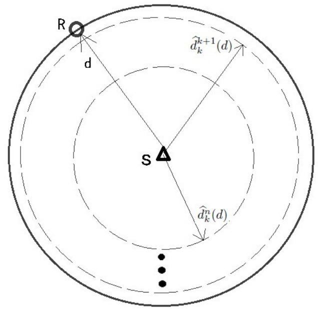

Fig. 1. Forwarding equivalent energy-efficiency distance (FEED)

no forwarding is performed between time t_k and t_n), the source can obtain the same forwarding energy efficiency as that of forwarding at time t_k. ■

Generally, we can calculate the FEEDs at time t_n $(n = k+1, k+2\cdots)$ as shown in Fig. 1. The engineering implications behind the FEED are as follows: if at a future time t_n there is at least i relays with a source-relay distance shorter than $\widehat{d}_k^{n,i}(d)$, then forwarding the packet copy now, at time t_k, leads to a lower forwarding energy efficiency than of waiting till t_n to forward the packet copy.

Lemma 1: For the broadcast transmission, if the source determines whether to forward the packet copy to q relays with a transmission radius d at time t_k, the FEED of broadcasting the packet copy to i relays at time t_n is

$$\widehat{d}_k^{n,i}(d) = d \cdot \sqrt[\alpha]{\frac{1-e^{-\lambda_R(T-t_n)\cdot i}}{1-e^{-\lambda_R(T-t_k)\cdot q}}}.$$

Proof: For the broadcast transmission, if the source forwards the packet copy to q relays with a transmission radius d at time t_k, the forwarding energy efficiency is $\eta_f(t_k) = \frac{(1-S(t_{k-1}))\cdot(1-e^{-\lambda_R(T-t_k)\cdot q})}{d^\alpha \cdot c}$. On the other hand, if the source determines not to forward the packet copy but to forward the packet copy to i relays at time t_n, then after forwarding, the increment of the packet delivery ratio is $\Delta S(t_n) = (1-S(t_{k-1}))\cdot(1-e^{-\lambda_R(T-t_n)\cdot i})$. According to Definition 2, we have

$$\begin{aligned}&\frac{(1-S(t_{k-1}))\cdot(1-e^{-\lambda_R(T-t_k)\cdot q})}{d^\alpha \cdot c}\\ =&\frac{(1-S(t_{k-1}))\cdot(1-e^{-\lambda_R(T-t_n)\cdot i})}{(\widehat{d}_k^{n,i}(d))^\alpha \cdot c}.\end{aligned} \tag{10}$$

Equivalently,

$$\widehat{d}_k^{n,i}(d) = d \cdot \sqrt[\alpha]{\frac{1-e^{-\lambda_R(T-t_n)\cdot i}}{1-e^{-\lambda_R(T-t_k)\cdot q}}}. \tag{11}$$

■

VI. Expectation-Based DEEOF Algorithm

Motivated by the above analysis, in this section we propose the DEEOF algorithm based on the expectation of the distance between the source and the relays (DEEOF-E), whose main idea is as follows: at each probing instance t_k, when there is at least one relay situated within the maximum transmission radius of the source, the source forwards the packet copy if the probability of achieving a higher forwarding energy efficiency in the future is below a threshold. In other words, the source determines to forward the packet copy if the probability that there are at least i relays whose distance to the source is smaller than $\widehat{d}_k^{n,i}(d)$ at time t_n $(n = k+1, k+2\cdots)$ is below a threshold for the broadcast transmission. The DEEOF-E algorithm calculates the probability of achieving a higher forwarding energy efficiency in the future according to the exponentially distributed IMT.

Since wireless communication is broadcast in nature, a single forwarding can transmit the packet copies to multiple relays within the transmission range of the source. Assume that at time t_k the source detects Q relays in its maximum transmission radius R; it establishes communication contact with them and measures the distance to the relays without a packet copy. Then the source ranks the relays without a packet copy in ascending order according to their distances and marks them with 1 to Q, whose distances are $\{d_q, 1 \le q \le Q\}$.

If the source forwards the packet copy in a broadcast manner with a radius d_q at time t_k, it will incur an energy consumption of $E_q(t_k) = {d_q}^\alpha \cdot c$. Since the q relays within the radius d_q will receive a packet copy after broadcasting, according to Definition 1, we obtain the forwarding energy efficiency of the broadcast as $\eta_f(t_k) = \frac{(1-S(t_{k-1}))\cdot(1-e^{-\lambda_R(T-t_k)\cdot q})}{d_q^\alpha \cdot c}$.

Therefore, the source calculates the forwarding energy efficiency of the broadcast with different transmission radii $d_q (1 \le q \le Q)$ in order, and chooses the transmission radius with which to obtain the highest forwarding energy efficiency. Without loss of generality, assume that forwarding the packet copy in a broadcast manner with a distance d_q can obtain the highest forwarding energy efficiency. According to Lemma 1, the FEED of broadcasting the packet copy to i relays at time t_n, denoted as $\widehat{d}_k^{n,i}(d_q)$, can be obtained.

Define random variable $\widehat{\varphi}_{t_{n-1},t_n}$ as an indicator, formally expressed as

$$\widehat{\varphi}_{t_{n-1},t_n} = \begin{cases} 1, & \text{At least } i \text{ relays within } \widehat{d}_k^{n,i}(d_q) \text{ during } [t_{n-1},t_n], \\ 0, & \text{otherwise.} \end{cases} \tag{12}$$

Thus we have

$$P\{\widehat{\varphi}_{t_{n-1},t_n} = 1\} = \sum_{i=1}^{m}\sum_{j=i}^{m} C_m^j (1-e^{-\lambda_{\widehat{d}_k^{n,i}(d_q)}\cdot U})^j \cdot (e^{-\lambda_{\widehat{d}_k^{n,i}(d_q)}\cdot U})^{m-j}. \tag{13}$$

Because of the memoryless property of exponential distribution, the probability of achieving a higher forwarding energy efficiency in the future, denoted as P_{better}, can be derived as follows:

$$\begin{aligned}P_{better} =& 1 - \prod_{n=k+1}\Bigg(1 - \sum_{i=1}^{m}\sum_{j=i}^{m} C_m^j (1-e^{-\lambda_{\widehat{d}_k^{n,i}(d_q)}\cdot U})^j \\ &\cdot (e^{-\lambda_{\widehat{d}_k^{n,i}(d_q)}\cdot U})^{m-j}\Bigg).\end{aligned} \tag{14}$$

The following pseudocode describes the DEEOF-E algorithm for the broadcast transmission. In the algorithm, θ is the

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threshold of P_{better} to make the forwarding decision, which has an impact on the tradeoff between the energy efficiency and packet delivery ratio: smaller θ increases energy efficiency at the price of degrading system performance, and vice versa.

Algorithm 1 DEEOF-E for Broadcasting: executed at the source at each contact time t_k

```
Initialization: Set threshold θ
if any relay in the maximum transmission radius then
    Measure the distance of the relays without a packet copy
    Rank these relays in ascending order according to their distances
    Calculate the transmission radius with which can obtain the greatest forwarding energy efficiency of broadcast
    Calculate FEEDs of broadcast at time t_n (n ≥ k+1) and P_better
    if P_better < θ then
        Forward the packet copy in broadcast manner
    else
        Do not forward the packet copy
    end if
end if
```

VII. Distribution-Based DEEOF Algorithm

In this section, we present the DEEOF algorithm based on the distribution of the distance between the source and the relays (DEEOF-D). The difference between the two DEEOF algorithms is that the DEEOF-D algorithm calculates the probability of achieving a higher forwarding energy efficiency in the future by deriving the probability of the relays situated in the FEED. The DEEOF-D algorithm can provide a more accurate prediction result by distribution analysis, and thus make more appropriate forwarding decisions.

In order to obtain the probability of the relays situated in the FEED, first we derive the distribution of the distance between the source and the relays.

Lemma 2: Assume that the stationary distributions of the location of the nodes are uniform[2], i.e.,

$$x_i \sim U(0, L) \quad \text{and} \quad y_i \sim U(0, L),$$

where (x_i, y_i) are the coordinates of the nodes. The cumulative distribution function (c.d.f.) of the distance r between the source and a relay is

$$F(r) = \frac{\pi r^2}{L^2} - \frac{8r^3}{3L^3} + \frac{r^4}{2L^4} \quad (0 \leq r \leq R).$$

Proof: If the nodes are located uniformly in the one-dimensional region, the probability distribution function (p.d.f.) of the distance is easily got.

$$f(d) = \frac{2}{L^2}(L - d), \tag{15}$$

where L is the region length and d is the distance between nodes. Now we consider the case in the two-dimensional region to derive the p.d.f. of the distance between two arbitrary nodes (x_1, y_1), (x_2, y_2). Let $x = |x_1 - x_2|$, $y = |y_1 - y_2|$, so we have

$$f_x(x) = \frac{2}{L^2}(L - x) \quad \text{and} \quad f_y(y) = \frac{2}{L^2}(L - y). \tag{16}$$

Since x and y are independent, the joint probability density function of x and y is

$$f_{xy}(x, y) = f_x(x) \cdot f_y(y) = \frac{4}{L^4}(L - x)(L - y). \tag{17}$$

In order to get the p.d.f. of the distance, we make the following transformation:

$$r = \sqrt{x^2 + y^2} \quad \text{and} \quad \phi = \arctan\frac{y}{x}, \tag{18}$$

where r is the distance between two nodes and ϕ is the angle. Thus the joint probability density function of r and ϕ is

$$f_{r\phi}(r, \phi) = \frac{f_{xy}(r\cos\phi, r\sin\phi)}{|J|}, \tag{19}$$

where J is the Jacobian:

$$J = \begin{vmatrix} \frac{\partial r}{\partial x} & \frac{\partial r}{\partial y} \\ \frac{\partial \phi}{\partial x} & \frac{\partial \phi}{\partial y} \end{vmatrix}_{x=r\cos\phi, y=r\sin\phi} = \frac{1}{r}. \tag{20}$$

Thus we have the following expression of $f_{r\phi}(r, \phi)$ as

$$f_{r\phi}(r, \phi) = \frac{4r}{L^4}(L - r\cos\phi)(L - r\sin\phi). \tag{21}$$

Taking the integral of ϕ, the p.d.f. of the distance between two nodes is obtained as

$$f(r) = \begin{cases} \frac{2\pi r}{L^2} - \frac{8r^2}{L^3} + \frac{2r^3}{L^4}, & 0 \leq r \leq L \\ \frac{4r(\frac{\pi}{2} - 2\arccos\frac{L}{r})}{L^2} \\ -\frac{8r(L - \sqrt{r^2 - L^2})}{L^3} + \frac{2r(2L^2 - r^2)}{L^4}, & L < r \leq \sqrt{2}L. \end{cases} \tag{22}$$

The source can only establish communication contact with the relays that move into its maximum transmission radius, so we consider the case of $0 \leq r \leq R$. Thus, the c.d.f. of the distance between the source and a relay is

$$F(r) = \int_0^r f(r)dr = \frac{\pi r^2}{L^2} - \frac{8r^3}{3L^3} + \frac{r^4}{2L^4} \quad (0 \leq r \leq R). \tag{23}$$

■

Let m denote the number of relays without any packet copies at time t_k, according to Lemma 2, the c.d.f. of the i-th nearest distance to the source among the m nodes, denoted as $F_R^i(r)$, can be derived as

$$F_R^i(r) = C_m^i (F(r))^i \cdot (1 - (1 - F(r))^{m-i}). \tag{24}$$

Assume that at time t_k, the source determines whether or not to forward the packet copy in a broadcast manner to the nearest q relays with a distance d_q, with which the source can obtain the greatest forwarding energy efficiency. According to Lemma 1, we can obtain the FEEDs of the broadcast $\widehat{d}_k^{n,i}(d_q)$ at time t_n $(n \geq k+1)$. Therefore, the probability of achieving

[2] If we possess the priori knowledge of the cumulative distribution function of the distance between two nodes or obtain the information by statistics, it is easy to extend our algorithm to other general cases.

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a higher forwarding energy efficiency in the future for the broadcast transmission case can be obtained as follows:

$$\begin{aligned} P_{better} =& 1-\prod_{n=k+1}\left(1-\sum_{i=1}^{m}F_R^i(\widehat{d}_k^{n,i}(d_q))\right) \\ =& 1-\prod_{n=k+1}\left(1-\sum_{i=1}^{m}C_m^i(F(\widehat{d}_k^{n,i}(d_q)))^i\right. \\ & \left.\cdot(1-(1-F(\widehat{d}_k^{n,i}(d_q)))^{m-i})\right). \end{aligned} \tag{25}$$

The pseudocode of the DEEOF-D algorithm for the broadcast transmission is almost the same as that of the DEEOF-E algorithm, except for the calculation of P_{better} and the threshold of P_{better}. Let ψ denote the threshold of P_{better} to make the forwarding decision, which has an impact on the balance of the tradeoff between the energy efficiency and packet delivery ratio.

VIII. Practical Considerations on Unavailable Forwarding Opportunities

We consider the DEEOF algorithms with the assumption that the opportunistic forwarding from the source to the relays is always successful in previous sections. However, in practical DTNs, there are a few issues making the forwarding opportunities unavailable.

1) Considering multiple neighboring nodes which transmit simultaneously [34] and conflict with each other, we consider the CSMA-like protocols [35][36] adopted to avoid the collision. The basic principle of CSMA-like protocols is listen-before-talk. In each probing time instance, the source utilizes the interference filtering property of the CSMA-like protocol before forwarding the packet copy to the relays. If the source senses the broadcast transmission of other nodes, the source will keep silence. Otherwise, the source will implement the DEEOF algorithms.
2) Considering the residual energy at the relays, we consider the opportunistic forwarding according to our proposed DEEOF algorithms only if both the transmitter and the receiver have enough energy for this transmission [24]. Furthermore, each relay reserves the energy for forwarding the packets which are already received, and rejects new forwarding requests if its residual energy is not sufficient.

Both cases lead to the situation where some of the relay nodes are unavailable for opportunistic forwarding. It can be treated as the case with a lower node density obtained by the statistics of the source node. We can extend the proposed DEEOF algorithms to the above cases. Denote p_c as the probability that either of the above two cases appear, which can be obtained by statistics.

For DEEOF-E algorithm, we just need to modify Eq. (14) as

$$\begin{aligned} P_{better} = 1-\prod_{n=k+1}\Bigg(1-(1-p_c) \\ \cdot\sum_{i=1}^{m}\sum_{j=i}^{m}C_m^j(1-e^{-\lambda_{\widehat{d}_k^{n,i}(d_q)}\cdot U})^j\cdot(e^{-\lambda_{\widehat{d}_k^{n,i}(d_q)}\cdot U})^{m-j}\Bigg). \end{aligned} \tag{26}$$

Similarly, for DEEOF-D algorithm, we modify Eq. (25) as

$$\begin{aligned} P_{better} = 1-\prod_{n=k+1}\Bigg(1-(1-p_c) \\ \cdot\sum_{i=1}^{m}C_m^i(F(\widehat{d}_k^{n,i}(d_q)))^i\cdot(1-(1-F(\widehat{d}_k^{n,i}(d_q)))^{m-i})\Bigg). \end{aligned} \tag{27}$$

IX. Simulation

In this section, we evaluate the performance of the proposed DEEOF algorithms for the broadcast transmission. Under the circumstances where the total battery reserve of the source is unconstrained, moderately constrained, and seriously constrained, we evaluate the performance of the DEEOF-E algorithm and the DEEOF-D algorithm by simulation using Matlab. For performance comparison, two existing algorithms are adopted as baselines.

- *Two-hop forwarding* [10]: The forwarding probability is 1 (indicated by “Always” in figures).
- *Threshold dynamic policy* [20]: The source just sends packet copies to relays before a time threshold (indicated by “Threshold” in figures).

The performance metrics include the average energy consumption, the packet delivery ratio, and the energy efficiency.

A. Simulation Configuration

In the simulation, 200 mobile nodes are deployed in the network, in which one source-to-destination pair is investigated for collecting simulation results. Each node’s movement is independent following the random direction mobility model. The maximum transmission radius is 15m and the mobile nodes move at a speed of 5m/s in a square of the size 600m×600m [37]. For the random direction mobility model, the corresponding value of λ_R is $5.3\times10^{-4}\mathrm{s}^{-1}$. We assume that the signal propagates in a free space propagation model, so from (3) we have $P_t=d^2\cdot c$. Without loss of generality, it is set as $c=1$. We set the slot duration to $U=1$s. For the circumstances where the energy is unconstrained, moderately constrained, and seriously constrained, the corresponding values of the total battery reserve of the source are 8000, 2000 and 500, respectively. The thresholds in the DEEOF-E algorithm and the DEEOF-D algorithm are set as 0.5.

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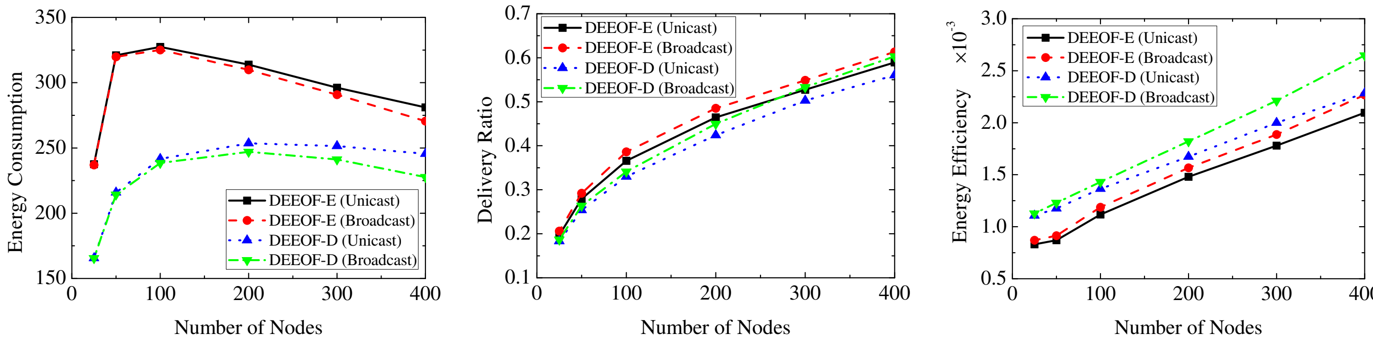


(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 2. Performance comparison of the DEEOF algorithms between the broadcast transmission and unicast transmission

B. Unicast vs. Broadcast

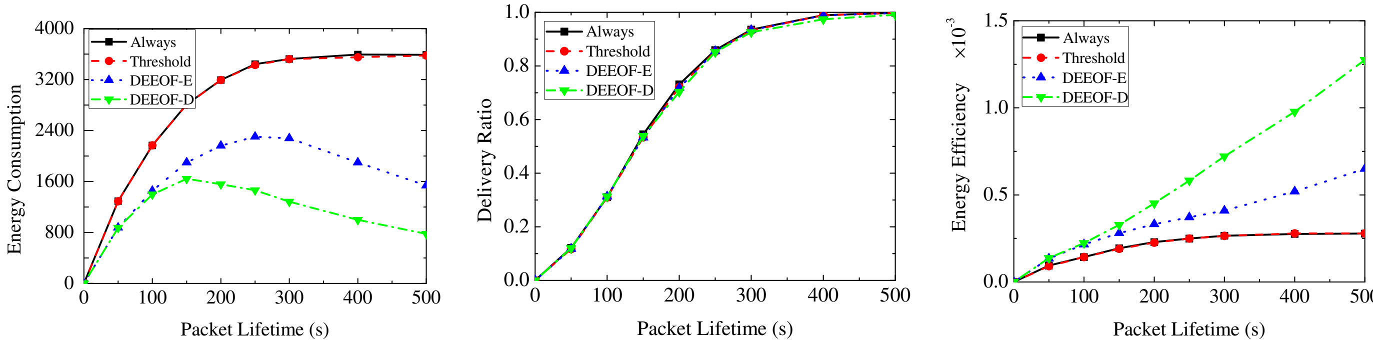
In order to show the performance improvement of the DEEOF algorithms for the broadcast transmission, we compare the performance of the DEEOF algorithms between the broadcast transmission and unicast transmission [29] with different numbers of mobile nodes. We obtain the performance comparison between the unicast and broadcast of the DEEOF with seriously constrained energy, as shown in Fig. 2. It can be observed that the broadcast transmission outperforms the unicast transmission, both in the DEEOF-E algorithm and the DEEOF-D algorithm. When the number of nodes is less than 100, there are few relays in the maximum transmission radius of the source at each probing instance. Consequently, the broadcast forwarding is almost the same with the unicast forwarding. In contrast, the performance superiority of broadcast over unicast can be observed with the increase of the number of nodes. With the increase of the number of nodes, the number of relays in the maximum transmission radius of the source at each probing instance increases. Consequently, the DEEOF-E algorithm and the DEEOF-D algorithm for the broadcast transmission, respectively, consume less energy and achieve both a higher packet delivery ratio and higher energy efficiency than that for the unicast transmission. Since wireless communication is broadcast in nature, a single forwarding can create copies in several nodes if the system supports the broadcast transmission. Although consuming the same amount of energy, the source may forward packet copies to more relays in a broadcast manner, which increases the delivery ratio as well as the energy efficiency.

C. Performance Comparison

In this subsection, we compare the performance of the DEEOF-E algorithm and the DEEOF-D algorithm for the broadcast transmission with two baseline protocols.

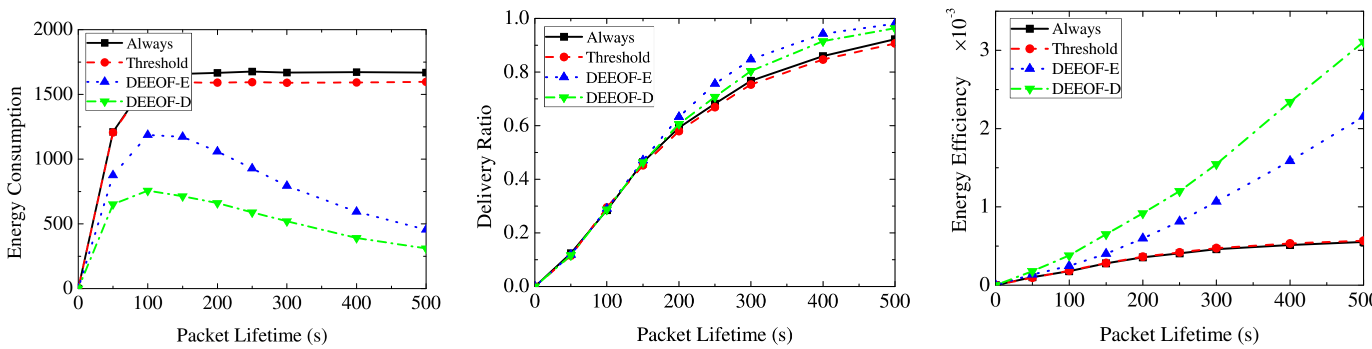
Fig. 3 shows the performance of the four forwarding algorithms with different packet lifetimes when the energy is unconstrained, i.e., E=8000. In this case, the packet delivery ratio of the four algorithms is almost the same. When the energy is sufficient, the source naturally prefers to forward more packet copies to improve the packet delivery probability. Consequently, the source forwards packets with probability 1 for the "Two-hop forwarding" and "Threshold dynamic policy" algorithms, leading to the highest delivery ratio regardless of packet lifetimes. For the DEEOF algorithms, the source can obtain the same delivery ratio with the other two algorithms, while the energy efficiency is much higher. When $T = 300$s and $T = 150$s, the average energy consumption of the DEEOF-E algorithm and the DEEOF-D algorithm, respectively, begin to decrease with the increase of T. The proposed DEEOF algorithms save above 50% energy compared to the other two algorithms when $T = 500$s. The reason is that for the DEEOF algorithms, the source determines whether to forward the packet copy to the relays by predicting the movement of the relays in the future. From (9), when T increases, the source should have a long-term consideration about the energy efficiency. Therefore it will predict a longer period of time, which leads to a more exigent requirement to forward to the relay; namely, the source requires the relays to be closer so that it can consume the energy more efficiently. It is foreseeable that when the energy is unconstrained, i.e., $E \to \infty$, then the predicted period δ will be zero according to (9), which leads the DEEOF algorithms to degrade to the "Two-hop forwarding". It can be also observed that the DEEOF-D algorithm achieves a higher energy efficiency but a slightly lower packet delivery ratio than the DEEOF-E algorithm with different packet lifetimes. This is related to the parameter θ in the DEEOFE algorithm and ψ in the DEEOF-D algorithm that we set. The thresholds can provide a balance of the tradeoff between the energy efficiency and packet delivery ratio as discussed in IX-D.

Fig. 4 shows the performance of the four forwarding algorithms with different packet lifetimes when the energy is moderately constrained, i.e., E=2000. The packet delivery ratio of the DEEOF algorithms are slightly higher than that of the other two algorithms over the packet lifetime. When the packet lifetime is less than 150s, the source has only very limited opportunities to meet the relays. Therefore, the energy of the source is largely sufficient in such scenario given the limited meeting opportunities. Consequently, as discussed in the response to the previous question, forwarding the packets to the relays with probability 1 leads to the highest delivery ratio. Again, for the DEEOF algorithms, the source can obtain the same delivery ratio with the other two algorithms, but consume less energy. The energy efficiency of the DEEOF algorithms



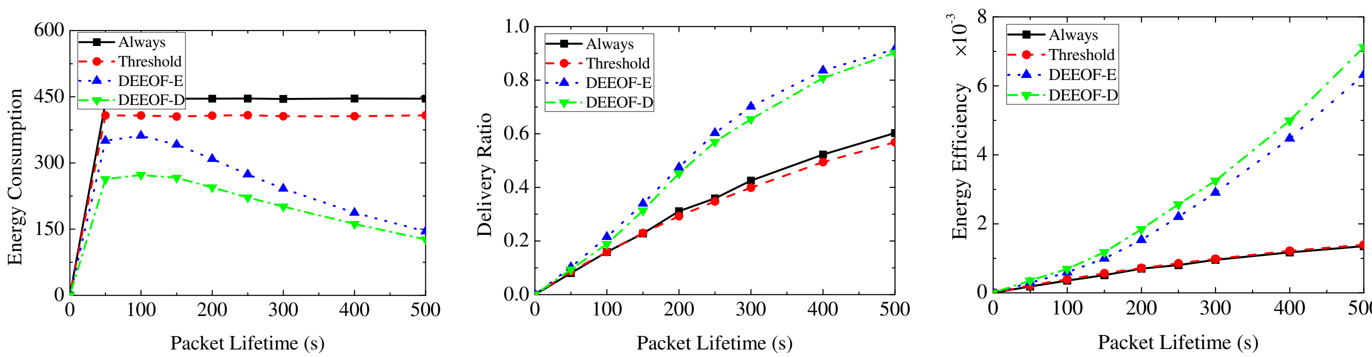
(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 3. Performance comparison with unconstrained energy (E=8000)



(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 4. Performance comparison with moderately constrained energy (E=2000)



(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 5. Performance comparison with seriously constrained energy (E=500)

is significantly higher than that of the other two algorithms, and is more than 3 times the other two when $T = 500$s. When $T = 500$s, our proposed DEEOF algorithms save above 70% energy compared to the two baseline algorithms.

Comparing Fig. 3(a) and Fig. 4(a), we observe that the average energy consumption of the DEEOF algorithms in the case of $E = 2000$ is much lower than that in the case of $E = 8000$. This is because for the proposed DEEOF algorithms, the source has a long-term consideration for energy efficiency when the energy is constrained, thus the source has a stringent requirement to forward to the relays.

Fig. 5 shows the performance of the four forwarding algorithms with different packet lifetimes when the energy is seriously constrained, i.e., E=500. In this case, we can find that the proposed DEEOF algorithms outperform the “Two-hop forwarding” and the “Threshold dynamic policy”. Compared with the baseline algorithms, the DEEOF algorithms consume less energy, and achieve both a higher packet delivery ratio and higher energy efficiency with different packet lifetimes. The dramatic improvement is that the packet delivery ratio of the DEEOF algorithms is about 50% higher than the other two baselines when $T = 500$s, and the energy efficiency is significantly higher. The reason is that for the other two baselines, once the relays move into the maximum transmission radius of the source, the source broadcasts the packet copies immediately with probability 1, without considering

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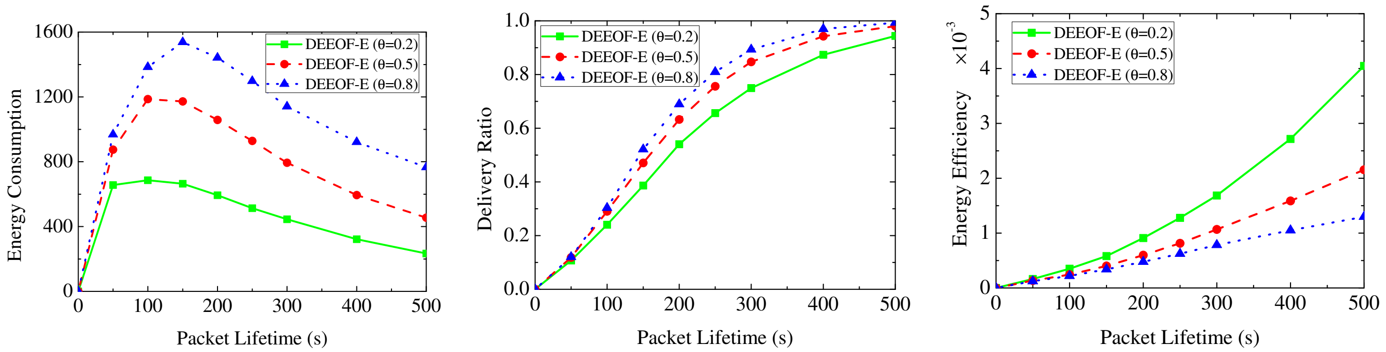
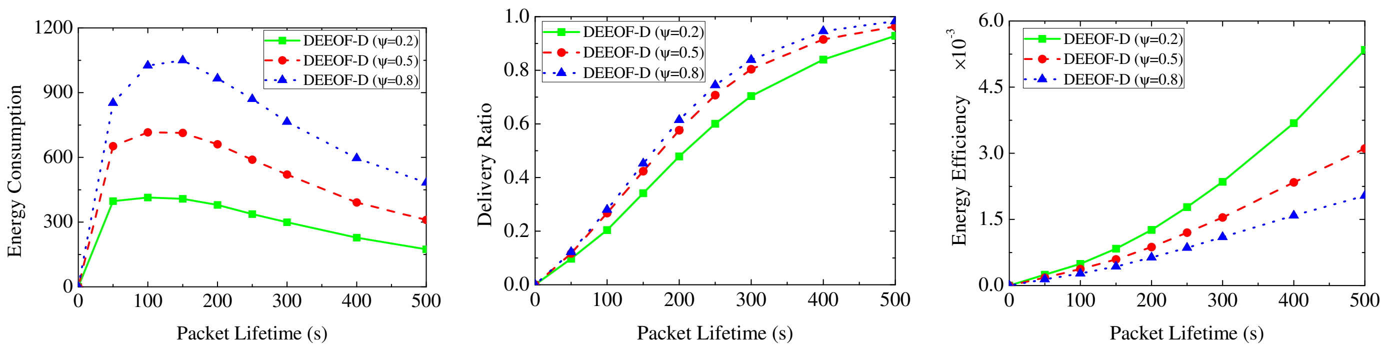


(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 6. Effect of θ in the DEEOF-E algorithm



(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 7. Effect of ψ in the DEEOF-D algorithm

whether the relays will continue to move closer. Although this forwarding scheme will not have a negative impact on the packet delivery ratio when the energy is unconstrained, the following situation could occur when the energy is seriously constrained: In the beginning, the source broadcasts the packets to any relays that move into its transmission range, even if the distance to the relay is the maximum transmission radius. After a certain period of time, even though other relays move close enough to the source, it can not forward the packet because the residual energy is not sufficient to complete the transmission. The DEEOF algorithms, however, are proposed under the consideration of the energy efficiency and packet delivery ratio specifically for the broadcast transmission; the source will broadcast the packet copy to the relays with the appropriate transmission radius if it predicts that the probability of achieving a higher forwarding energy efficiency in the future does not reach the set threshold.

D. Tradeoff Between Energy Efficiency and Packet Delivery Ratio

As analyzed previously, the parameter θ in the DEEOF-E algorithm and ψ in the DEEOF-D algorithm can provide a balance of the tradeoff between the energy efficiency and packet delivery ratio. Fig. 6 and Fig. 7 show the performance comparison with a varying θ value and ψ value in the DEEOF-E algorithm and the DEEOF-D algorithm, respectively, when $E = 2000$. It is found that in Fig. 6, small θ increases energy efficiency at the price of degrading the packet delivery ratio, and vice versa. This is because the DEEOF-E algorithm with smaller θ prefers a higher forwarding energy efficiency of the current time rather than the estimated future expectation; i.e. the source has a more stringent requirement to forward to the relays. Similar results can be observed in Fig. 7. Therefore, the tradeoff between the energy efficiency and packet delivery ratio can be balanced by adjusting θ and ψ in the DEEOF algorithms according to the service requirements.

E. Performance Comparison with Unavailable Forwarding Opportunities

Fig. 8 shows the performance of the four forwarding algorithms with unavailable forwarding opportunities caused by either conflict avoidance or energy reservation. The probability that the forwarding opportunity is unavailable in each timeslot is set to $p_c = 0.5$. It is found that in this more practical scenario, the DEEOF algorithms also consume less energy, and achieve both a higher packet delivery ratio and higher energy efficiency compared with the baseline algorithms.

F. Evaluation with Real Vehicular Mobility Trace

In this subsection, we adopt the real vehicular mobility trace from about 3400 cars in the city of Cologne, Germany [38] for the performance evaluation. The location information of the cars is recorded at every 1s within the area of 400 km^2. We employ the maximum transmission radius $R = 100$m, as

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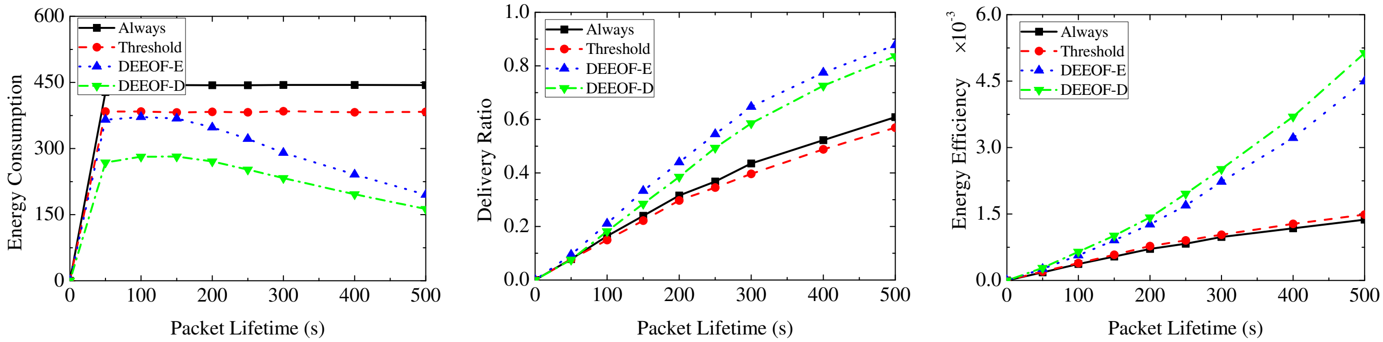
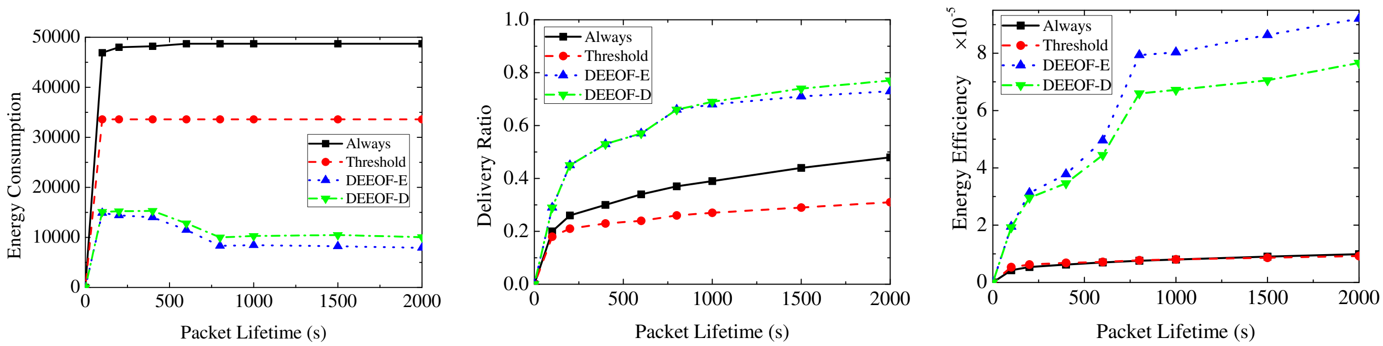


(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 8. Performance comparison with seriously constrained energy (E=500) with unavailable forwarding opportunities



(a) average energy consumption (b) packet delivery ratio (c) energy efficiency

Fig. 9. Performance comparison with E=50000 in the real vehicular ad hoc networks scenario

this is the value referenced by field tests as a typical distance for reliable vehicle-to-vehicle communication [39]. The value of λ_R is $5.6 \times 10^{-4}\text{s}^{-1}$, which is obtained from the trace data by statistics.

Fig. 9 shows the performance of the four forwarding algorithms in the real vehicular ad hoc networks scenario with different packet lifetimes when $E = 50000$. It can be found that the proposed DEEOF algorithms outperform the "Two-hop forwarding" and "Threshold dynamic policy" algorithms. Compared with the two baseline algorithms, the DEEOF algorithms consume less energy, and achieve both a higher packet delivery ratio and higher energy efficiency with different packet lifetimes.

X. Conclusion

In this paper, we propose two DEEOF algorithms for the broadcast transmission to maximize both the energy efficiency and packet delivery ratio. Exploiting the node mobility, opportunistic forwarding is based on the transmission distance in order to achieve energy efficiency. The concept of the FEED is developed by comparing the current energy efficiency and the estimated future expectation. The DEEOF algorithms make forwarding decisions based on the FEED. Simulation results show that our proposed DEEOF algorithms greatly improve the energy efficiency while maintaining a high packet delivery ratio compared to the existing forwarding algorithms. The performance gain of our algorithms is particularly significant for systems where the source has very limited battery reserves.

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